Brown Dwarfs and the TW Hya Association

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ABSTRACT

I report the results of a survey for low-mass ($0.030 \gtrsim M \gtrsim 0.013 M_\odot$) brown dwarfs in the direction of the TW Hya association using 2MASS. Two late-M dwarfs show signs of low surface gravity and are strong candidates to be young, very-low-mass ($M \approx 0.025 M_\odot$) brown dwarfs related to the TW Hya association. 2MASSW J1207334-393254 is particularly notable for its strong Hα emission. The numbers of detected brown dwarfs is consistent with the substellar mass function in richer star formation environments. Newly identified late-M and L dwarfs in the field are also discussed. Unusual objects include an L dwarf with strong Hα emission, a possible wide M8/M9 triple system, and a possible L dwarf companion to an LHS star.

Subject headings: stars: low-mass, brown dwarfs — open clusters and associations: individual (TW Hya Association) — stars: activity

1. Introduction

The Two Micron All-Sky Survey (2MASS), the Deep Near-Infrared Survey (DENIS), and the Sloan Digital Sky Survey (SDSS) have identified large numbers of cool dwarfs in the field. This has led to the development of the new L dwarf spectral class (Kirkpatrick et al. 1999; Martín et al. 1999), corresponding to temperatures in the range $\sim 1400 - 2200$K. The observed numbers of L dwarfs imply that isolated field brown dwarfs are common though even if the details of the substellar mass function remains uncertain (Reid et al. 1999). Observations of rich star-forming regions have also identified numerous young brown dwarf candidates (see the review of Basri 2000).

Recent work has identified nearby ($d \lesssim 100$ pc) associations of very young (< 100 Myr) stars (Jayawardhana & Greene 2001). The most notable of these new associations is the TW Hya association (TWA), a loose group of T Tauri stars with an age of ~ 10 Myr (Webb et al. 1999; Makarov & Fabricius 2001). These nearby T Tauri and post-T Tauri stars allow unique studies of star formation processes due to their proximity and brightness. Furthermore, they offer insights into

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star formation in a low-density enviroment that differs from the dominant star formation process observed in dense star regions like Orion.

The identification of young brown dwarfs in TWA and similar associations promises to advance substellar astronomy — confirming that isolated brown dwarfs form in a low-density star formation environment and providing bright, nearby prototypes for follow-up studies. Current optical and X-ray surveys were only sensitive to ordinary stars ($M \gtrsim 0.2 M_{\odot}$). Nevertheless, one young TWA brown dwarf is known: TWA 5B is an M8 secondary identified by Hubble Space Telescope imaging about 100 A.U. from its primary star (Lowrance et al. 1999). The apparent magnitude, $H = 12.1$, of TWA 5B is well above the 2MASS magnitude limits ($H \approx 15.1$ for signal-to-noise 10, Cutri et al. 2000); any similar, *isolated* TWA brown dwarfs will therefore appear in the 2MASS survey. Furthermore, TWA is in a relatively clean field away from the Galactic plane and without background reddened sources.

I present the results of a 2MASS-based search for isolated, very-low-mass brown dwarfs in the TW Hya association. I present the search criteria and follow-up spectroscopy in Section 2. The results are discussed in Section 3.

2. Sample Selection and Spectroscopy

2.1. Photometric Selection

The 2MASS survey provides precise and accurate photometry in the J, H, and K_s bands. Kirkpatrick et al. (1999) and Gizis et al. (2000) discuss the selection of late-M and L dwarfs using the 2MASS surveys. M dwarfs in the range M0-M7 have similar near-infrared colors ($J - K_s \approx 0.9$) which makes it difficult to efficiently select M6 and M7 dwarfs. In contrast, M8 through late-L dwarfs are characterized by redder 2MASS colors ($J - K_s > 1.0$) which distinguish them from most background stars. The addition of optical colors from the POSS and other optical surveys allow nearly all contaminating populations (mostly extragalactic at high galactic latitude) to be eliminated. I therefore chose to concentrate on these M8 and cooler L dwarfs in this initial search for TWA candidates. Because the hydrogen burning limit at this age will lie near spectral class M6 (Luhman 1999), this strategy allows only the cooler and hence lower mass brown dwarfs to be detected, roughly corresponding to masses $M < 0.03 M_{\odot}$.

Figures 1 and 2 illustrate the initial sample selection using the 2MASS Working Database. This database includes the entire sky but represents only the preliminary processing of the 2MASS dataset. The area searched (Figure 1) was chosen to encompass the TWA members listed by Webb et al. (1999), Sterzik et al. (1999) and Zuckerman et al. (2001). The photometric selection (Figure 2) was designed to include potential late-M and L dwarfs members on the basis of their $J - K_s$ colors. The position of TWA 5B is marked in Figure 2 as a T. Luhman (1999) has found that the young brown dwarfs in IC 348 (age $\lesssim$ 10 Myr) have J-H,H-K colors similar to the field population. The

limiting magnitude for targets was a function of J-K_s:

$$K_s < 2.5 \times (J - K_s) + 9.5 \tag{1}$$

As shown in Figure 2, this selection would include any other M/L dwarfs that follow the observed field M/L dwarf sequence slope found by Gizis et al. (2000) and extends 1.1 magnitudes fainter at K_s than TWA 5B. This allows for the inclusion of brown dwarfs further away than TWA 5B, or the possibility that TWA 5B is overluminous due to being an unresolved double. The limiting magnitude for the survey corresponds to $\sim 0.013 M_\odot$ assuming bolometric corrections similar to field dwarfs (Chabrier et al. 2000) — this limiting mass is of course uncertain due to both theoretical and observational limitations. Each 2MASS source was examined on the DSS sky survey scans at the CADC web site. Those with bright optical counterparts ($B \lesssim 19$) were excluded since M8 and later dwarfs will be red. The targets are listed in Table 1. The J2000 positions encoded in the official 2MASS names are accurate to an arcsecond.

2.2. Other Field Dwarfs

Late in the night, the TWA region was not accessible during the CTIO observing run. I therefore selected candidate nearby field M and L dwarfs using the 2MASS Working database. The targets observed are listed in Table 2. All targets are required to have $J - K_s > 1.0$ and no bright optical counterpart. A number of other known field M and L dwarfs were observed, most notably the recent discovery DENIS-P J104814.7-395606.1 (Delfosse et al. 2001). I find a spectral type of M8 for this star, slightly earlier than the M9 previously estimated in the discovery paper from high resolution observations. TVLM 868-53850, an M dwarf discovered by Tinney (1993), is a near-infrared standard star (Persson et al. 1998; Nikolaev et al. 2000) that has not been previously observed spectroscopically. It is an M5.0 with strong Hα emission (7.0Å). A careful examination of the 2MASS calibration observations of this star might reveal if the high chromospheric activity leads to any near-infrared variability. The standards VB8, LHS 2397a, LHS 2065, and 2MASSW J1507476-162738 as well as some earlier M dwarfs were also observed. No flares were noted in these dwarfs.

2.3. Spectroscopy

The targets were observed using the R-C spectrograph on the CTIO 4-meter Blanco telescope on UT Dates 30 April to 3 May 2001. Despite the faintness of the targets, even the L dwarfs were visible in the acquisition camera. The wavelength coverage was 6430 to 9700 Å with a FWHM resolution of $\sim$ 2.8Å. Flux standards from Hamuy et al. (1994) were observed. The spectral extraction and calibration was made using standard IRAF routines.

To aid in spectral classification, spectral indices were measured. These included TiO5 (Reid, Hawley & Gizis 1995; Gizis 1997), PC3 (Martín et al. 1999), CrH, TiO-b, Cs-a, VO-a and VO-b

(Kirkpatrick et al. 1999). Spectral types were adopted based on these indices and visual inspection of the spectra. All spectral types are on the Kirkpatrick, Henry, & McCarthy (1991) and Kirkpatrick et al. (1999) M and L dwarf scale. The equivalent width of Hα was measured when emission was present. The adopted spectral types and equivalent widths are included in Tables 1 and 2. The measured indices are given in Table 3, where multiple measurements of the same object have been averaged. In Figure 3, some of the measured indices are plotted as a function of adopted spectral type. The signal-to-noise and resolution of the spectra are not adequate to search for lithium.

3. Discussion

3.1. Two TW Hya Association Late-M Brown Dwarfs?

Young brown dwarfs, particularly TWA brown dwarfs, will have low surface gravity. Luhman, Liebert, & Rieke (1997) and Martín, Rebolo, & Zapatero-Osorio (1996) discuss the characteristics of young late-M brown dwarfs. They are characterized by stronger VO and weaker hydrides and Na lines than ordinary field M dwarfs. In Figure 4, the surface gravity sensitive indices are plotted against spectral type. Only two late-M objects show both strong VO and weak Na and CaH. This can be seen in Figure **??**, where the specrtra of these two objects are compared to the ordinary field M8 dwarf LHS 2397a and the **?** ρ Oph brown dwarf. A few objects show an anomalous VO index but their other indices and the overall appearance of their spectra do not support low surface gravity; I attribute these anomalies to noise and do not consider them further. The two candidate TW Hya brown dwarfs are discussed below.

2MASSW J1207334-393254: This M8 dwarf shows signatures of low surface gravity, which indicates that it is a young ($\lesssim$ 100 Myr) brown dwarf. Confirmation of TW Hya membership requires space motion information. I have examined the United States Naval Observatory Image and Catalogue Archive for sky survey images of 2MASSW J1207334-393254. The oldest image, taken in 1964, has the poorest detection. The images show motion of 100 mas yr^{-1} west and 30 mas yr^{-1} south relative to other stars in the field; this motion is consistent with TWA membership (Mamajek, private comm.). On the basis of this proper motion and the spectroscopy, 2MASSW J1207334-393254 therefore may be regarded as a probable member of the TW Hya association, although CCD astrometry is needed to strengthen this conclusion.

In any case, the proper motion is considerably smaller than most 2MASS late-M dwarfs (Gizis et al. 2000), supporting a young age.

2MASSW J1207334-393254's most notable characteristic, however, is its extremely strong Hα emission (Figure 5). The equivalent width of Hα emission in two consecutive 900 second exposures was 300Å. Helium emission at 6678Å is also detected with an equivalent width of 3Å. A powerful flare such as the one observed by Liebert et al. (1999) could account for the Hα emission, but would have weakened by the second exposure and produced additional atomic emission lines. Since these

characteristics are not observed, it is unlikely that this emission is caused by a flare.

Strong but persistent Hα emission is not seen in field 2MASS late-M dwarfs (Kirkpatrick et al. 1999; Gizis et al. 2000), but is known in three late-M systems. Two of these systems, the M8 brown dwarf ρ Oph 162349.8-242601 (Luhman, Liebert, & Rieke 1997) and the M7 brown dwarf CFHT-BD-Tau J043947.3+260139 (Martín et al. 2001), are young brown dwarfs whose emission is attributed to an accretion disk. If due to the same cause, then 2MASSW J1207334-393254's emission supports a young age and probable TW Hya membership. Figure 5

Strong Hα emission is also known in another, still mysterious, M9 dwarf. The dwarf PC 0025+0447 was discovered by Schneider et al. (1991) due to its Hα emission ($EW \approx 300$Å) which has persisted for a decade. 2MASSW J120733-393254's Hα and HeI emission are very similar to Martín, Basri & Zapatero Osorio (1999)'s spectra of PC 0025+0447 in its relatively inactive, unveiled state. Martín, Basri & Zapatero Osorio (1999) argue that PC0025+0447 is a young brown dwarf with an age between 10 and 100 Myr and that the emission is due to chromospheric/coronal activity. Such a scenario might also apply for 2MASSW J1207334-393254 and would be consistent with TWA membership.

2MASSW J1139511-315921: A second M8 dwarf, 2MASSW J1139511-315921, is also a low surface gravity brown dwarf and therefore a candidate TWA member. The $H\alpha$ emission is weaker, with $EW = 9.7$Å, but He 6678Å emission is present with $EW \approx 1.9$Å. Weak emission is typical of young brown dwarfs. Examination of the USNO scans reveals a proper motion consistent with ~ 110 mas yr^{-1} to the south and ~ 110 mas yr^{-1} to the west. This motion is inconsistent with the TWA and other young clusters, except perhaps the Pleiades (Mamajek, private comm.). Nevertheless, given the weak detections and resulting astrometric uncertainty 2MASSW J1139511-315921 may still be a TWA member. Comparison to the Chabrier et al. (2000) models suggests that both 2MASSW J1207334-393254 and 2MASSW J1139511-315921 have masses $\sim 0.025 M_\odot$ if members; Lowrance et al. (1999) finds the same result for the similar TWA 5B.

3.2. L Dwarf Candidates

Seven L dwarfs were detected in the TWA search. If any of these L dwarfs were TWA members, they would have very low mass and low surface gravity. Martín et al. (1999) have compared the L2 dwarf G196-3B, believed to have an age of ~ 100 Myr, with older field L dwarfs of similar spectral type. It shows weaker TiO, CrH, FeH, Na, K, Cs and Rb. It is likely that ~ 10 Myr old early-L dwarfs will show similar, but greater, anomolies. No later very low-surface gravity L dwarfs are known, but it seems likely they would have also have significant differences with respect to ordinary field L dwarfs. Since none of the observed L dwarfs show compelling evidence for low surface gravity, I conclude they are not TWA members, but three deserve special discussion. Measurement of the proper motions of the L dwarfs would be relatively easy over the next few years and would indicate if any are actually TWA members.

2MASSI J1315309-264951: The L5 dwarf 2MASSI 1315309-264951 is an intriguing object because it shows strong Hα emission (Figure 6). Because of the very low continuum levels, the equivalent width of ~ 100Å is highly uncertain. The relative energy in Hα is $\log(H\alpha/L_{bol}) = -3.9$. This L dwarf is ~ 100 times more active than the *upper limits* for late-L dwarfs in Gizis et al. (2000). It was observed with six consecutive 600 second exposures on 01 May and two consecutive 900 second exposures on 02 May. The emission is constant over those time periods and it is therefore unlikely that the emission is due to a flare. The J-K_s color of 1.7 is not unusual for the spectral type of L5.

2MASSI J1315309-264951 was independently discovered by Hall (2002), who discribes two spectra. Hall (2002) found strong emission on 30 March 2001 with EW$\approx$ 100Å, but much weaker emission (EW $\approx$ 25Å) in a lower-quality spectrum in August 2001.[2] Hall (2002) gives a discussion of the possible analogs and explanations for the emission. Hall favors the explanation that the March emission is due to a flare. Given the match of the emission in the May spectra, this now appears to be an unlikely possibility. Confirmation of the low activity state seen in August is desirable. Hall discusses the possibility that 2MASSI J1315309-264951 may be an analog to the Te dwarf 2MASSW 1237392+652615 (Burgasser et al. 2000). Since, like the Te dwarf, 2MASSI J1315309-264951 does not show signs of low surface gravity, it is likely a hotter analog of the still not-yet- understood Te dwarf rather than a very young (TW Hya) brown dwarf. As noted by Hall (2002), analogies to the active late-M dwarfs with persistent emission (such as LHS 2397a) may also be appropriate. The correlations found by Gizis et al. (2000) would then suggest that 2MASSI J1315309-264951 may be a relatively old L dwarf (perhaps even burning hydrogen!). I note that Mullan & MacDonald (2001) have presented nonstandard interior models with strong magnetic fields in which magnetically active L dwarfs might actually be stars. The possible proper motion noted by Hall would be inconsistent with TW Hya membership and would suggest a relatively old kinematic age. Further study – particularly astrometry – of this intriguing L dwarf is needed to understand its evolutionary status. If, despite the arguments already given, this L dwarf is a TWA member, comparison of Chabrier et al. (2000)'s model calculations to its K_s magnitude and effective temperature would suggest a mass of $\sim 0.013 M_\odot$, near the deuterium burning limit.

Kelu-1: The TWA search criteria selected the well-known L dwarf Kelu-1 (Ruiz, Leggett, & Allard 1997), which is known to lie above other dwarfs in the HR diagram, but whose astrometric distance and motion (Dahn et al. 2002) is inconsistent with the TW Hya association.

2MASSW J1155395-372735: The L2 dwarf, like Kelu-1, shows weak Hα emission. The emission was present with similar strength on two different nights. It is brighter than Kelu-1 and may serve as a useful L dwarf for further study.

[2]Note that Hall (2002) assigns a spectral type of L3, but the spectra reported are nearly identical to the L5 2MASSW J1507476-162738.

3.3. The Mass Function

There are five known TW Hya members in the range 0.5 to 0.9 $M_\odot$ and 10 in the range 0.2 to 0.5 $M_\odot$, consistent with a power-law mass function ($\frac{dN}{dM} \propto M^{-\alpha}$) with slope $\alpha = 1$. Extrapolation of this mass function, which is consistent with field and cluster studies, predicts ~ 4 brown dwarfs in the range 0.015 to 0.025 $M_\odot$. The observations of two strong candidate isolated brown dwarf in this mass range are consistent with this distribution. (Note that one might also count the wide companion TW Hya 5B.) In contrast, a mass function slope of $\alpha = 0$ would predict only 0.1 such brown dwarfs. Within the very large uncertainties due to the small sample size, there is no evidence for an IMF in the TW Hya association that differs from richer star formation regions (typically $\alpha \approx 0.5 - 1.0$). Studies of the outskirts of the TWA area and searches of other associations are needed to build up useful statistics.

3.4. Comments on Field Dwarfs

Most of the field M and L dwarfs observed in this program have properties consistent with those observed in previous 2MASS surveys. The unusual emission of the L dwarf was discussed in Section 3.2. Two other systems deserve special discussion.

2MASSW J1004392-333518: This L4 dwarf, discovered in the TWA search, is 7.4 arcsec east and 9.6 arcsec south of the high proper motion star LHS 5166. The relationships in Kirkpatrick et al. (2000) predict $M_J = 12.940$ and $M_K = 11.326$ for an L4 dwarf, both consistent with a distance of 21 pc. At this distance, the separation of the two components is 250 A.U. No proper motion is available for the L dwarf since it is not detected on the sky survey plates, so companionship is *not* confirmed. The CTIO 4-meter spectrum reveals that LHS 5166 is an M4 dwarf with Hα emission of 2.6Å. The 2MASS photometry is $J = 9.859$, $H = 9.336$, and $K_s = 9.035$. This spectral type is at the position of a kink in the main sequence: at LHS 5166's TiO5 index value of 0.39, the main sequence covers the range $6.5 < M_K < 8.5$ (Gizis & Reid 1996). The L dwarf's distance estimate implies $M_K = 7.43$ (if the components are single), which is consistent with the large uncertainties for M4 dwarfs. At spectral type M4, 31% of stars have $H\alpha$ emission (Hawley et al. 1996); if star formation is constant over 10 Gyr, then the system is probably no older than ~ 3.1 billion years old.

2MASSW J1510478-281817: An M9 dwarf, 2MASSW J151047-281823, is 3.3 arcseconds west and 5.9 arcseconds south of the M8 dwarf 2MASSW J151047-281817. The proximity suggests that this may be a binary system, although the differences in magnitude ($\Delta J = 1.16$, $\Delta H = 1.22$, $\Delta K_s = 1.07$) are surpisingly large given the one class difference in spectral type. The M8 has $H\alpha$ emission ($EW = 2.5$Å) while the M9 does not, but this is consistent with fall-off in activity with spectral type (Gizis et al. 2000) and does not rule out binarity. The M8 has a photometric distance estimate of 20 parsecs ($M_K = 10.19$, assuming it is on the main sequence) while the M9's estimate is 30 parcsecs ($M_K = 10.39$); the corresponding orbital separation would then be 135 or 200 A.U.

If the M8 is an equal luminosity double then the discrepency would be explained. Approximately 20% of 2MASS-selected late-M dwarfs are doubles when imaged by Hubble Space Telescope (Gizis et al., in prep.), so this scenario is plausible. The USNO scans do not have a clear detection of the M9 dwarf, and therefore do not reveal whether the proper motions are consistent. Additional data are required to show that this a physically related system rather than a chance alignment. If confirmed by common proper motions and radial velocities, this would be widest known system composed only of M8 or later components.

4. Summary

A 2MASS-based search for isolated TWA brown dwarfs has found two late-M brown dwarfs which are candidate TWA members. None of the L dwarfs observed appear to be TWA members. These observations are consistent with the substellar mass function seen in richer star formation regions. One young M8 dwarf shows very strong emission features and is an ideal candidate for more detailed study of this rare phenomenon; a number of other dwarfs identified in this search are also unusual and deserve additional follow-up.

This pilot study has confirmed that 2MASS is useful for identifying young brown dwarf members of nearby associations. Extension of this study to either higher mass brown dwarfs of spectral type M6-M7 and very-low-mass brown dwarfs of spectral type T (below the deuterium burning limit) is practical but requires additional imaging and spectroscopy.

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Table 1. TWA Targets

Name	J	H	K_s	Sp.	Hα EW
2MASSW J1004392-333518	14.505	13.493	12.932	L4	···
2MASSW J1012065-304926	12.235	11.620	11.139	M6	5.6
2MASSW J1013426-275958	12.271	11.643	11.261	M5.0	6.6
2MASSW J1018588-290953	14.218	13.440	12.816	L1	···
2MASSW J1032136-420856	12.855	12.241	11.834	M7	11.8
2MASSW J1036530-344138	15.635	14.462	13.806	L6	···
2MASSW J1039183-411033	11.962	11.337	10.941	M6	4.4
2MASSW J1045171-260724	12.818	12.138	11.611	M8	6.0
2MASSW J1046040-304842	12.566	11.897	11.565	M5.5	10.8
2MASSW J1052012-501444	13.325	12.609	12.174	M8	4.7
2MASSW J1117540-515302	10.665	9.766	9.279	gM	···
2MASSW J1119195-403813	10.395	9.575	9.162	gM	···
2MASSW J1122362-391605	15.717	14.689	13.898	L3	···
2MASSW J1132137-264724	14.874	14.169	12.960	AGN	13.1
2MASSW J1135238-493527	15.400	14.485	13.692	AGN	···
2MASSW J1139511-315921	12.673	11.990	11.490	M8[a]	10.0
2MASSW J1141423-334133	13.854	12.778	12.177	C	···
2MASSW J1144249-430253	12.214	11.579	11.180	M6	···
2MASSW J1148259-380927	11.154	10.508	10.127	M5.0	···
2MASSW J1148542-254440	13.408	12.679	12.172	M8	17.8
2MASSW J1153063-250544	12.894	12.221	11.869	M5.0	4.4
2MASSW J1155395-372735	12.830	12.044	11.437	L2	2.5
2MASSW J1201544-293248	12.823	12.239	11.802	M6	4.9
2MASSW J1202410-445538	11.964	11.015	10.708	gM	···
2MASSW J1205527-385451	12.477	11.883	11.467	M5.0	···
2MASSW J1206235-401708	13.268	12.619	12.189	M8	1.4
2MASSW J1207334-393254	12.982	12.396	11.959	M8[a]	300
2MASSW J1208247-420400	11.802	10.900	10.572	gM	···
2MASSI J1211024-261409	15.267	14.349	13.163	QSO	···
2MASSW J1223135-492544	12.324	11.667	11.317	M5.0	···
2MASSW J1229430-352302	11.985	11.079	10.817	gM	···
2MASSW J1238292-405608	15.379	13.914	12.734	C	···
2MASSW J1241080-384312	11.470	10.833	10.447	M5.0	10.8

Table 1—Continued

Name	J	H	K_s	Sp.	Hα EW
2MASSW J1241552-315259	12.720	12.029	11.639	M6.5	7.7
Kelu-1	13.417	12.387	11.726	L2	1
2MASSI J1315309-264951	15.184	14.055	13.457	L5	97
2MASSW J1324055-350806	13.384	12.669	12.270	M6	···
2MASSW J1325580-362035	12.363	11.734	11.321	M5.0	8.3
2MASSW J1326201-272937	15.835	14.717	13.841	L5	···
2MASSI J1326401-421912	11.697	10.767	10.484	gM	···
2MASSW J1329019-414713	13.657	12.817	12.339	M9	···

[a]Low surface gravity (see Section 3.1)

Table 2. Field Targets

Name	J	H	K_s	Sp.	Hα EW
2MASSI J1003191-010507	12.352	11.685	11.267	M7	16.4
2MASSW J1045171-260724	12.818	12.138	11.611	M8	6.0
2MASSI J1045240-014957	13.129	12.370	11.810	L1	···
DENIS-P J104814.7-395606.1	9.551	8.915	8.452	M8	2.0
2MASSW J1054119-850502	12.716	12.065	11.657	M8	···
2MASSI J1224522-123835	12.564	11.831	11.371	M8	11.3
2MASSI J1309218-233035	11.769	11.087	10.666	M7	6.7
2MASSI J1359206-302339	14.577	13.072	11.798	C	···
2MASSW J1420544-361322	11.484	10.853	10.406	M7	7.0
2MASSI J1421187-161820	12.769	12.109	11.675	M8	···
2MASSI J1504162-235556	12.025	11.389	11.031	M7	5.5
2MASSW J1510168-024107	12.625	11.838	11.371	M8	4.2
2MASSW J1510476-281823	14.011	13.332	12.767	M9	···
2MASSW J1510478-281817	12.848	12.114	11.693	M8	2
2MASSW J1515110-133227	12.594	11.516	10.785	C	···
2MASSI J1534570-141848	11.390	10.731	10.311	M8	2.6
2MASSW J1555157-095605	12.531	11.993	11.451	L1	3.1
2MASSW J1558187-205419	12.037	11.406	10.967	M5.5	19.8
2MASSW J1607312-044209	11.882	11.176	10.717	M8	7.9
2MASSW J1611453-192813	12.871	12.187	11.814	M5.0	10.5
2MASSW J1614232-125046	13.034	12.435	11.983	M7	5.0
2MASSW J1632588-063148	12.757	12.044	11.628	M7	6.6
2MASSW J1635369-114710	12.913	12.229	11.817	M3	···
2MASSW J1645221-131951	12.467	11.723	11.195	L1.5	···
2MASSI J1652277-160738	13.130	12.130	11.525	C	1.1
2MASSW J1655379+045430	12.364	11.759	11.282	M8	2.8
2MASSW J1707234-055824	12.062	11.274	10.710	M9	0.4
2MASSW J1832238-443508	12.978	12.370	11.918	M6	7.1
2MASSW J1930274-194349	12.390	11.731	11.283	M6.5	6.0

Table 3. Spectral Indices

Name	TiO5	PC3	CrH	TiO-b	VO-a	VO-b
Gl 300	0.40	1.13	0.96	1.23	0.99	1.03
Gl 369	0.74	1.01	1.00	1.04	0.99	0.99
Gl 831A	0.37	1.16	0.97	1.28	1.00	1.04
Kelu-1	1.05	2.72	1.55	1.24	1.03	1.15
LHS 2065	0.51	2.23	1.07	2.02	1.20	1.51
LHS 2397a	0.34	2.10	1.10	2.11	1.15	1.48
LHS 5166	0.39	1.16	0.99	1.21	1.00	1.01
TVLM 868-53850	0.27	1.33	0.99	1.50	1.03	1.13
VB 8	0.17	1.67	1.04	1.88	1.08	1.27
2MASSW J1003191-010507	0.24	1.81	1.10	1.99	1.09	1.34
2MASSW J1004392-333518	1.11	4.38	1.91	1.27	0.82	1.04
2MASSW J1012065-304926	0.23	1.57	0.99	1.84	1.08	1.29
2MASSW J1013426-275958	0.30	1.33	0.98	1.47	1.01	1.11
2MASSW J1018588-290953	0.86	2.65	1.35	1.49	1.08	1.25
2MASSW J1032136-420856	0.22	1.88	1.12	2.01	1.09	1.34
2MASSW J1036530-344138	0.84	65.57	1.83	0.91	0.33	0.98
2MASSW J1039183-411033	0.26	1.47	1.02	1.59	1.04	1.15
2MASSW J1045171-260724	0.26	1.96	1.06	2.22	1.19	1.51
2MASSW J1045240-014957	0.99	2.71	1.35	1.52	1.10	1.29
2MASSW J1046040-304842	0.24	1.39	1.00	1.54	1.04	1.13
2MASSW J1052012-501444	0.23	2.06	1.11	2.25	1.17	1.51
2MASSW J1054119-850502	0.29	2.16	1.08	2.27	1.15	1.51
2MASSW J1117540-515302	0.30	1.15	0.90	1.49	0.97	1.05
2MASSW J1119195-403813	0.32	1.03	0.90	1.43	0.95	1.03
2MASSW J1122362-391605	0.81	4.39	1.65	1.21	1.14	1.09
2MASSW J1132137-264724	0.99	0.87	0.99	1.02	0.98	1.00
2MASSW J1135238-493527	1.33	1.03	1.00	1.01	0.98	0.97
2MASSW J1139511-315921	0.26	2.02	0.91	2.56	1.33	1.71
2MASSW J1141423-334133	0.60	0.79	0.90	0.88	1.11	1.10
2MASSW J1144249-430253	0.22	1.46	0.96	1.65	1.05	1.19
2MASSW J1148259-380927	0.31	1.29	0.94	1.46	1.02	1.12
2MASSW J1148542-254440	0.43	2.14	1.04	2.25	1.16	1.52
2MASSW J1153063-250544	0.26	1.35	1.01	1.42	1.02	1.08

Table 3—Continued

Name	TiO5	PC3	CrH	TiO-b	VO-a	VO-b
2MASSW J1155395-372735	0.98	3.00	1.62	1.35	1.03	1.22
2MASSW J1201544-293248	0.23	1.51	0.97	1.82	1.07	1.26
2MASSW J1202410-445538	0.71	1.03	0.99	1.04	0.98	1.00
2MASSW J1205527-385451	0.25	1.34	0.96	1.54	1.04	1.14
2MASSW J1206235-401708	0.32	1.90	1.00	2.23	1.17	1.54
2MASSW J1207334-393254	0.29	1.80	0.92	2.38	1.25	1.60
2MASSW J1208247-420400	0.52	1.03	0.97	1.12	0.97	0.99
2MASSW J1211024-261409	1.27	0.84	0.99	0.97	1.03	1.06
2MASSW J1223135-492544	0.26	1.33	0.93	1.57	1.05	1.17
2MASSW J1224522-123835	0.40	1.96	1.02	2.19	1.20	1.55
2MASSW J1229430-352302	0.26	1.06	0.85	1.73	0.95	1.09
2MASSW J1235366-411203	1.07	1.01	1.02	1.00	1.01	0.99
2MASSW J1238292-405608	0.93	1.08	1.04	0.98	1.02	1.04
2MASSW J1241080-384312	0.29	1.41	0.99	1.62	1.05	1.19
2MASSW J1241552-315259	0.23	1.58	0.98	1.92	1.11	1.34
2MASSW J1309218-233035	0.24	1.89	1.02	2.11	1.14	1.45
2MASSW J1315309-264951	1.33	9.12	2.04	1.06	0.79	1.07
2MASSW J1324055-350806	0.23	1.49	0.96	1.84	1.12	1.33
2MASSW J1325580-362035	0.29	1.26	0.95	1.51	1.02	1.13
2MASSW J1326201-272937	0.86	17.23	1.89	1.06	0.35	1.01
2MASSW J1326401-421912	0.35	1.07	0.92	1.36	0.97	1.01
2MASSW J1329019-414713	0.69	2.12	1.05	1.69	1.20	1.40
2MASSW J1359206-302339	0.77	0.97	1.01	1.01	1.10	0.95
2MASSW J1420544-361322	0.20	1.75	1.08	2.00	1.10	1.33
2MASSW J1421187-161820	0.26	1.94	1.16	1.95	1.07	1.32
2MASSW J1504162-235556	0.21	1.69	1.04	1.95	1.11	1.33
2MASSW J1507477-162738	1.12	7.50	2.14	1.11	0.89	1.01
2MASSW J1510168-024107	0.41	2.11	1.15	2.12	1.18	1.51
2MASSW J1510478-281817	0.30	2.01	1.00	2.46	1.30	1.71
2MASSW J1515110-133227	0.52	0.83	0.92	0.91	1.11	1.03
2MASSW J1534570-141848	0.19	2.05	1.12	2.20	1.10	1.38
2MASSW J1555157-095605	0.74	3.31	1.44	1.68	1.10	1.42
2MASSW J1558187-205419	0.26	1.39	0.90	1.77	1.05	1.23

Table 3—Continued

Name	TiO5	PC3	CrH	TiO-b	VO-a	VO-b
2MASSW J1607312-044209	0.27	1.94	1.04	2.13	1.18	1.48
2MASSW J1611453-192813	0.28	1.33	0.92	1.56	1.01	1.14
2MASSW J1614232-125046	0.17	1.67	1.04	1.91	1.10	1.30
2MASSW J1632588-063148	0.25	1.99	1.11	2.17	1.14	1.49
2MASSW J1635369-114710	0.47	1.17	0.98	1.14	0.99	1.00
2MASSW J1645221-131951	0.87	2.89	1.45	1.46	1.07	1.27
2MASSW J1652277-160738	0.53	0.92	0.92	0.90	1.14	0.95
2MASSW J1655379+045430	0.23	2.19	1.12	2.26	1.12	1.44
2MASSW J1707234-055824	0.60	2.43	1.19	1.91	1.18	1.48
2MASSW J1832238-443508	0.25	1.47	1.00	1.71	1.06	1.22
2MASSW J1930274-194349	0.23	1.65	1.04	1.92	1.10	1.31

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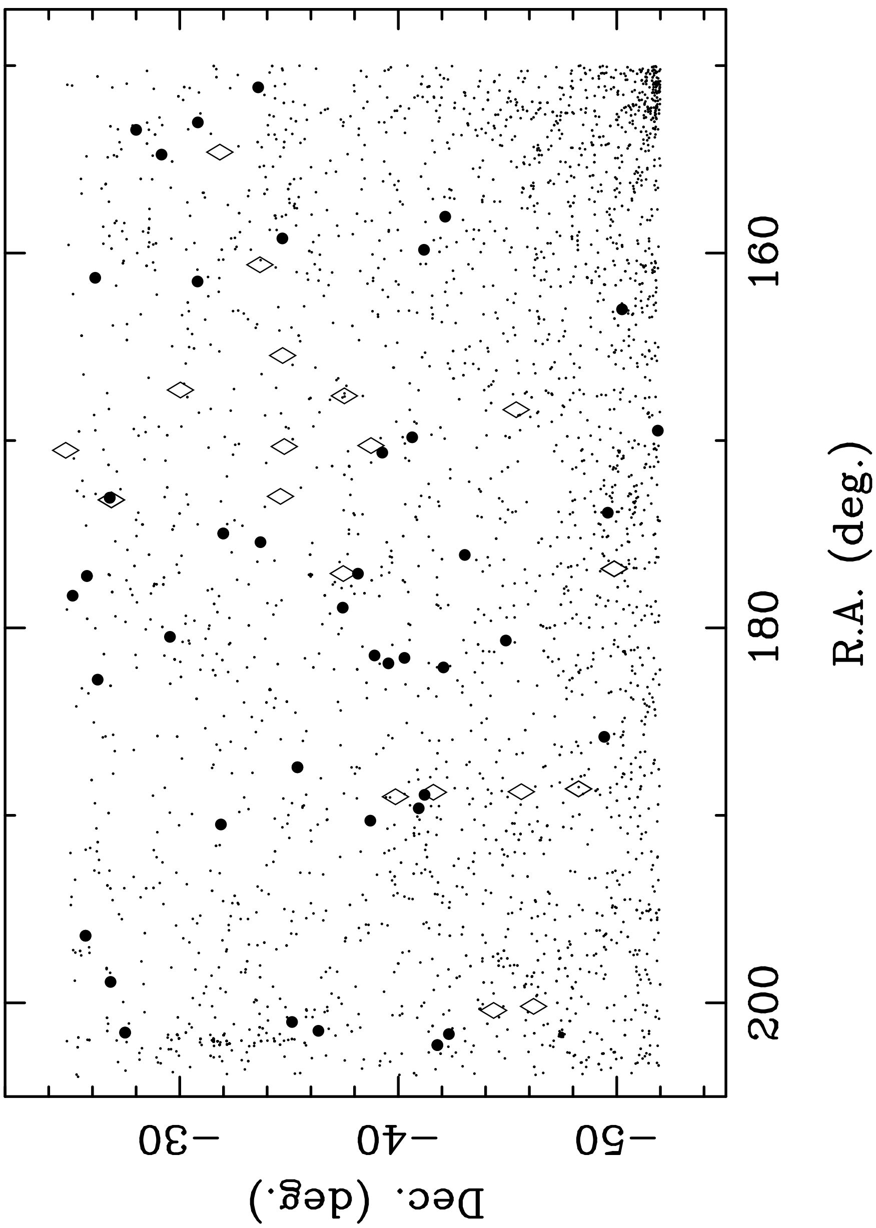

Fig. 1.— Spatial distribution of known TWA members (open diamonds), and candidate M/L dwarfs for this program (solid circles).

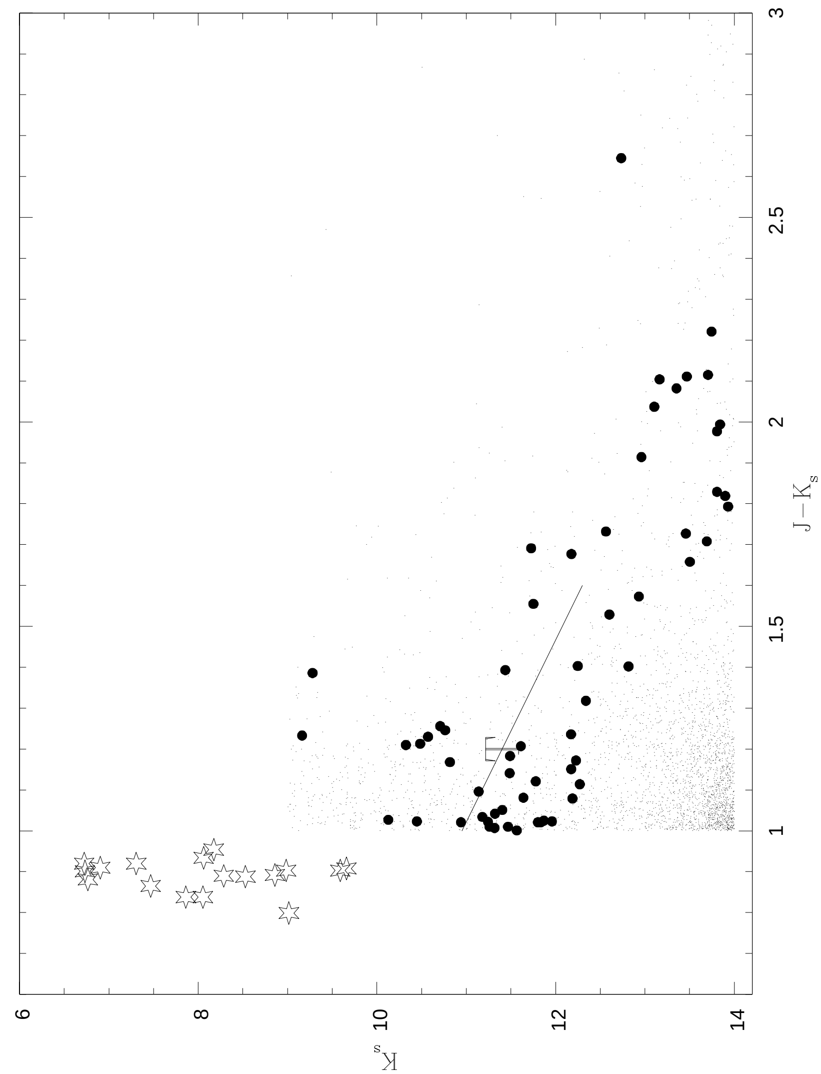

Fig. 2.— The 2MASS color-magnitude diagram including known TWA members (open stars), candidate M/L dwarfs for this program (solid circles), and other red background 2MASS sources (small points) with optical counterparts. The data for brown dwarf TWA 5B (Lowrance et al. 1999) is marked as a large 'T.' The solid line plots the observed field M/L color-magnitude relation shifted to agree to TWA 5B.

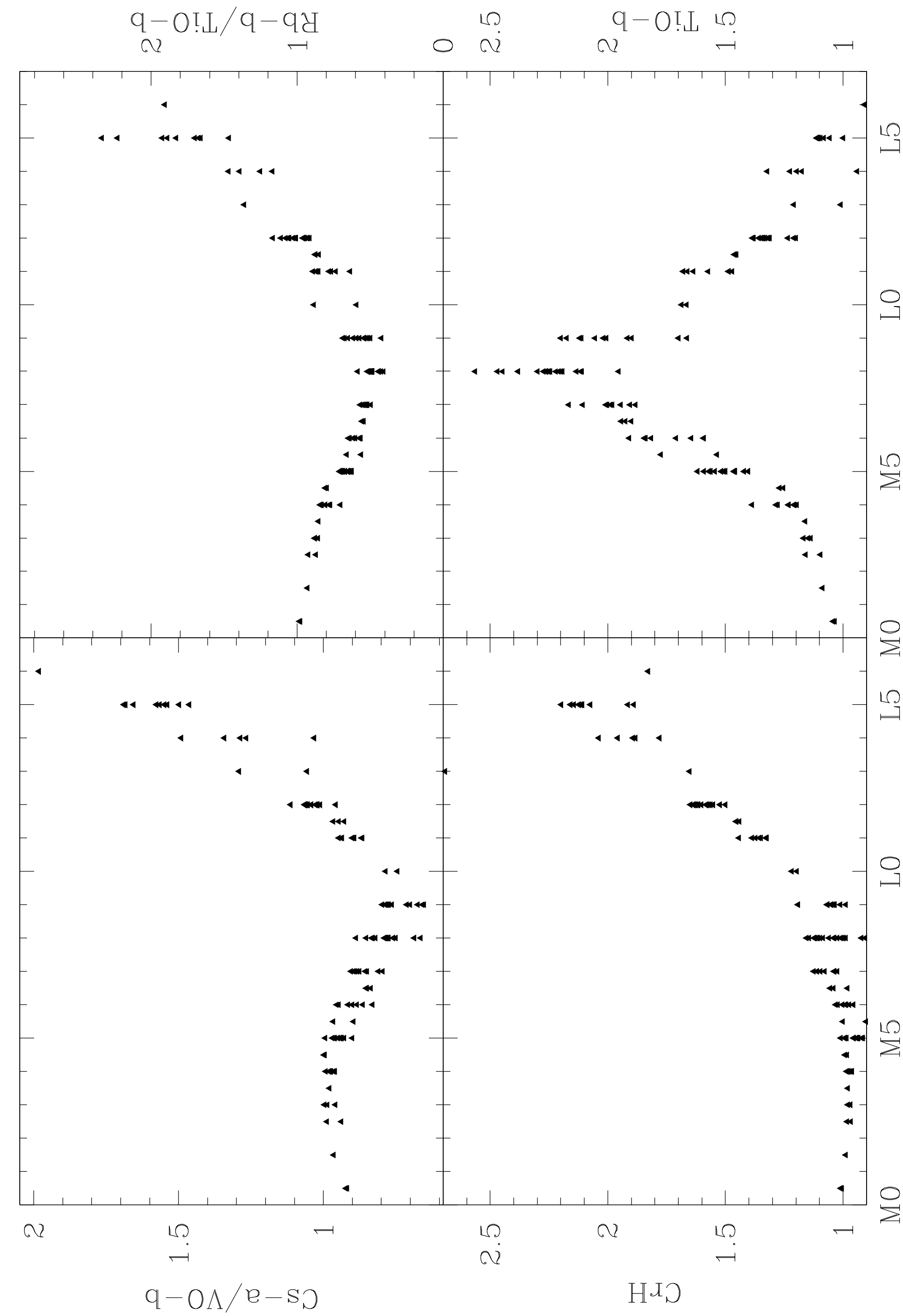

Fig. 3.— Spectral indices plotted as a function of spectral type. Each measurement of a star is plotted.

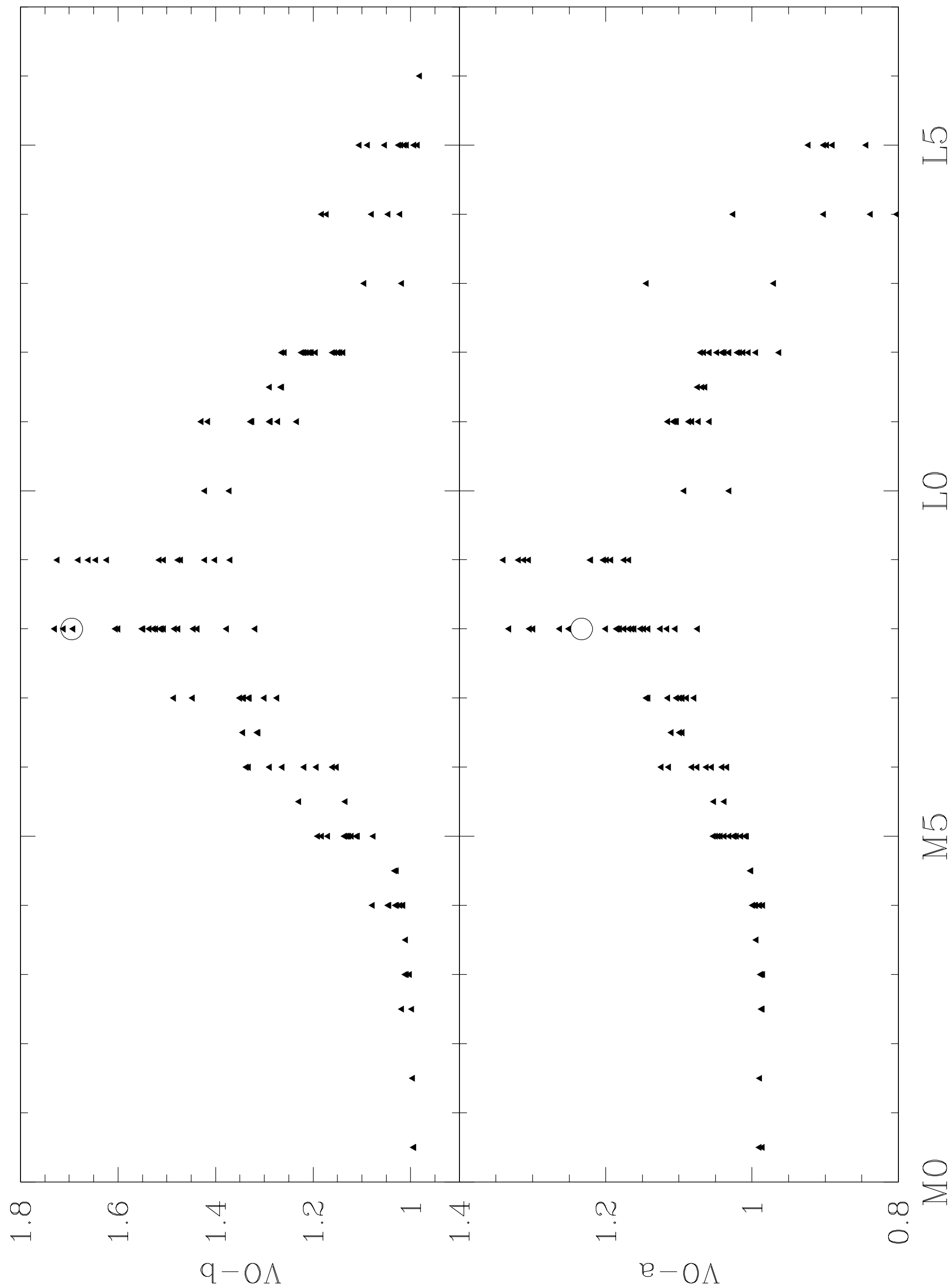

Fig. 4.— Measured VO-a and VO-b indices as a function of spectral type. Luhman (1999)'s brown dwarf is shown as an open circle. Two dwarfs show evidence of strong VO and hence low surface gravity, both in the TW Hya region. Each measurement of a star is plotted.

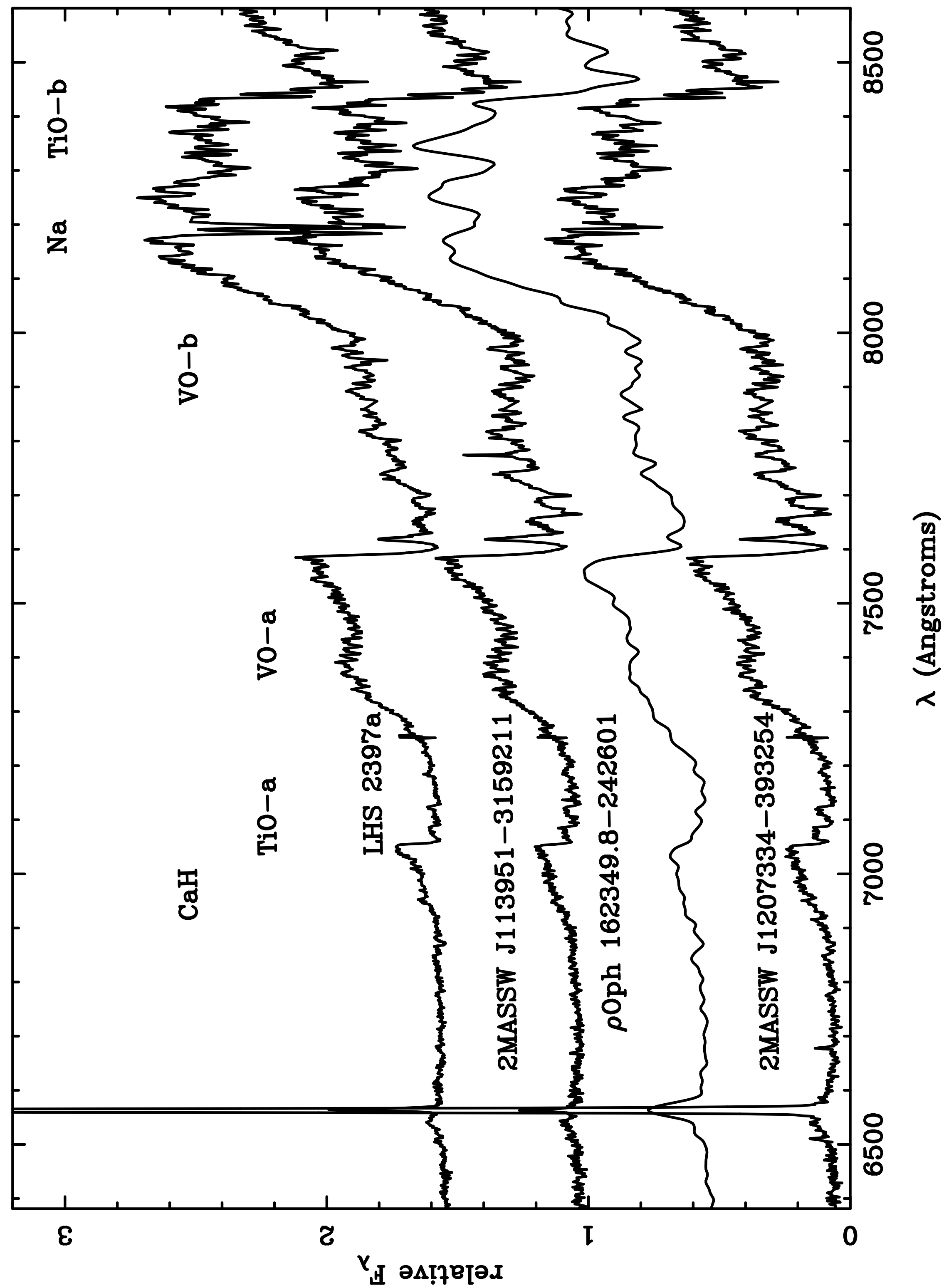

Fig. 5.— Luhman (1999)'s ρ Oph brown dwarf and the young brown dwarf candidates 2MASSW J1207334-393254 and 2MASSW J1139511-315921. The field M8 dwarf LHS 2397a is also shown. Note the weak CaH, weak Na, and strong VO compared to the field dwarf.

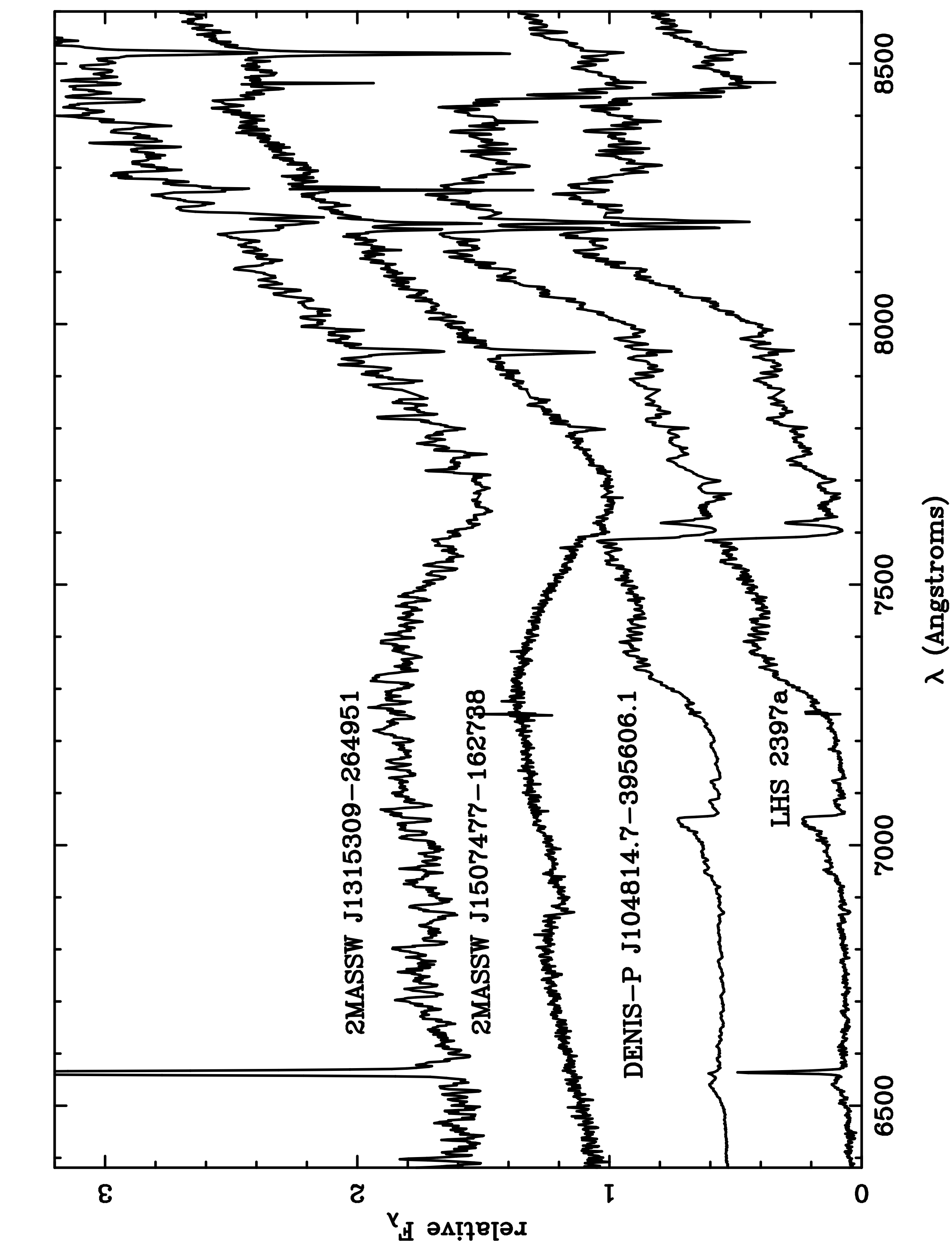

Fig. 6.— The active L dwarf 2MASSI J1315309-264951 (boxcar smoothed) compared to the field L5 dwarf 2MASSW J2MASSW J1507477-162738 and the nearby M dwarf DENIS-P J104814.7-395606.1 compared to the M8 dwarf LHS 2397a.